WFIRST Coronagraph Key Level 3 Requirements: Threshold and Baseline

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Threshold L3 Requirements

- **Threshold requirements correspond to minimum science yield necessary for WFIRST CGI mission success (beyond technology demo)**

- **Can be defended at the SRR/MDR with margin, based on demonstrated CGI performance, existing CGI design and components**

- **Threshold L3 performance currently is:**
  - Static contrast achieved in the lab (with bright pseudo-star)
  - 10% bandwidth (as tested)
  - WFIRST pupil
  - Throughput of the tested design
  - 5x post-processing gain
  - EMCCD detector performance at mission end-of-life (6 yrs)
    - JPL standard Radiation Design Factor (RDF = 2)

- **Using these parameters in CGI yield model (Nemati & SIT's) to evaluate integration time to SNR per target**

Baseline L3 Requirements

- **CGI is a tech demo flight instrument**

- **CGI optical/electrical/mechanical design will be matured and frozen per NASA flight practices, along with the requirements for the key hardware components:**
  – Low noise detector
  – Deformable mirror (DM)
  – Fast steering mirror (FSM)
  – Other mechanisms

- **However, key aspects of CGI performance are determined by coronagraphic masks and wavefront control algorithms that can continue to evolve:**
  – "Drop in" coronagraphic masks validated on the testbed can be installed during CGI I&T (2021)
    - **Increasing effective planet throughput is the focus of ongoing optimizations**
  – Improved DM wavefront control algorithms can be uploaded as late as Phase E (on orbit operations)
  – Improved Low Order Wavefront Control algorithms for DM and FSM can be uploaded as late as Phase E
  – Data post-processing algorithms will be developed and improved into Phase E

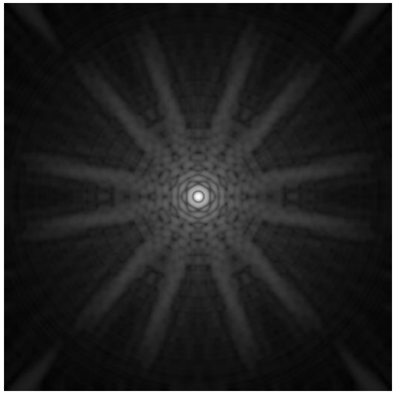
Improving coronagraph throughput

Telescope obscurations diffract light outside of the planet's PSF core into the wings. For WFIRST, 34% of the planet's light is within the core (FWHM region). This is called the *PSF core throughput*.

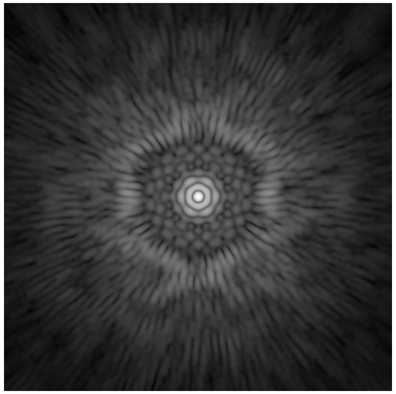
Coronagraph masks reduce the flux by blocking light, but they also diffract even more light out of the core into the wings (as do the large-stroke DM patterns in the HLC). The light in the wings is essentially lost in the noise, reducing the effective throughput of the system. Improving the core throughput has been a top goal for designers.

$$\text{relative core throughput} = \frac{\text{flux in planet's core with coronagraph}}{\text{flux in planet's core without coronagraph}}$$

WFIRST
PSF
(no coronagraph)



WFIRST
HLC PSF



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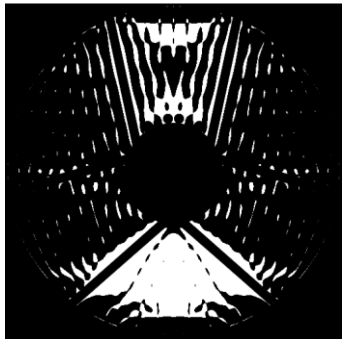
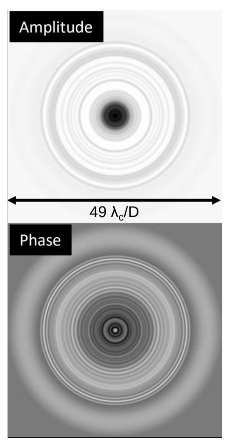
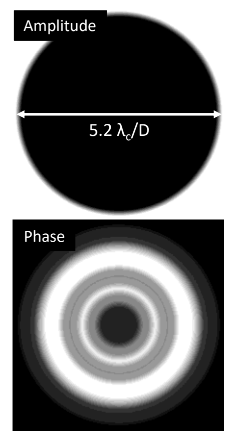
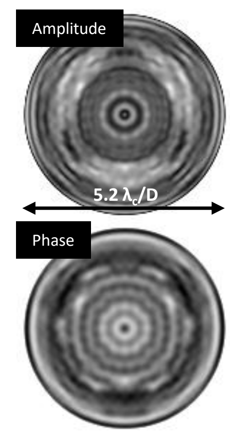
WFIRST CGI Design Improvements

	Downselect 2013	Revised 2014	Current 2017
Shaped Pupil Coronagraph pupil mask shown			
Relative core throughput =	7.9%	10.9%	20.6%
Field radius =	4.0 – 22.5 λ_c/D	2.8 – 9.0 λ_c/D	3.0 – 8.7 λ_c/D
Hybrid Lyot Coronagraph focal plane mask shown			
Relative core throughput =	7.9%	12.6%	18.5%
Working angle radius =	3.8 – 13.2 λ_c/D	3.0 – 10.0 λ_c/D	3.0 – 9.0 λ_c/D

CGI L3 Requirements: 565nm Imaging Mode

Requirement Name	Threshold Value	Baseline Value
CGI Mode: Imager/HLC, 565nm, 10% BW		
Core Throughout	0.01	0.02
Inner working angle, l/D	3	2.8
Bandpass, %	10	10
Raw Contrast, 3-4 l/D	6.00E-09	2.00E-09
Raw Contrast, 4-5 l/D	3.00E-09	1.00E-09
Raw Contrast, 5-9 l/D	2.00E-09	1.00E-09
Post-processing Gain	5x	10x
Detector Performance	CCD201 after 6 yrs, RDF = 2	CCD201 after 3 yrs, RDF = 1

Baseline vs. Threshold: Comments

- Core throughput here incudes: coatings, masks, PSF shape, polarizer.
- Assumes 2x core throughput increase from threshold to baseline design. (Latest design provides 1.5x improvement.)
- Need to revisit the advantage of digging dark hole in one polarization -- trade 2x better throughput vs shallower contrast.
- Assumes slight IWA improvement in the baseline design.
- Contrast informed by MS9 data. Assumes 0.5 mas residual pointing jitter. Improvement between threshold and baseline is mainly due to reduction of jitter sensitivity. Informed by MS9 data.
- Baseline detector requirements: same detector, taking advantage of opportunity to use it earlier in the mission, and reduced RDF to 1.

CGI L3 Requirements: 660 nm Spectroscopy Mode

Requirement Name	Threshold Value	Baseline Value
CGI Mode: IFS/SPC, 660nm, 18% BW		
Core Throughout	0.009	0.018
Inner working angle, l/D	2.8	2.8
Bandpass, %	10	18
Raw Contrast, 3-4 l/D	9.00E-09	6.00E-09
Raw Contrast, 4-5 l/D	7.00E-09	4.00E-09
Raw Contrast, 5-9 l/D	5.00E-09	4.00E-09
Post-processing Gain	5x	10x
Detector Performance	CCD201 after 6 yrs, RDF = 2	CCD201 after 3 yrs, RDF = 1

CGI L3 Requirements: 770 nm Spectroscopy Mode

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Requirement Name	Threshold Value	Baseline Value
CGI Mode: IFS/SPC, 770nm, 18% BW		
Core Throughout	0.009	0.018
Inner working angle, l/D	2.8	2.8
Bandpass, %	10	18
Raw Contrast, 3-4 l/D	1.00E-08	7.00E-09
Raw Contrast, 4-5 l/D	8.00E-09	5.00E-09
Raw Contrast, 5-9 l/D	5.00E-09	4.00E-09
Post-processing Gain	5x	10x
Detector Performance	CCD201 after 6 yrs, RDF = 2	CCD201 after 3 yrs, RDF = 1

Yield suffers in 770nm vs. 660nm IFS band due to

1) Lower detector QE
2) Larger IWA
3) Larger polarization-induced astigmatism
4) Detector fringing

CGI Detector Requirements

- **These are the noise and efficiency requirements for the WFIRST coronagraph detector. Functionality requirements also apply. The coronagraph Science investigation teams will be defining the threshold science case. We expect that the capability-based requirements below will meet the threshold science.**
- **The basis of these requirements is the already-achieved end of life EMCCD performance, as well as a detection and characterization SNR model.**
- **The following conditions must be applied when evaluating detectors against these requirements:**
  A. Detector is at the end of life for the WFIRST mission (6 years at L2)
  B. Incident flux from all photon sources is e-/pixel/frame
  C. Detection is in the photon counting mode
  D. The detector is no colder than -105º C or 168 K

1. Conversion Efficiency

– Defined as the fraction of times a single incident photon is counted as a single photon and includes
  - Quantum Efficiency
  - Charge transfer efficiency (where applicable)
  - Photon counting efficiency (thresholding efficiency)

Conversion efficiency	Imaging 1	Imaging 2	IFS 1	IFS 2
	450 nm	565 nm	660 nm	770 nm
	10%	10%	18%	18%
@	23%	24%	23%	18%

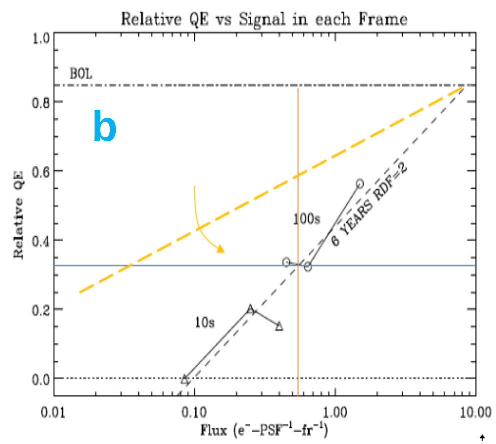
2. Total Noise from one pixel in a 100-second frame

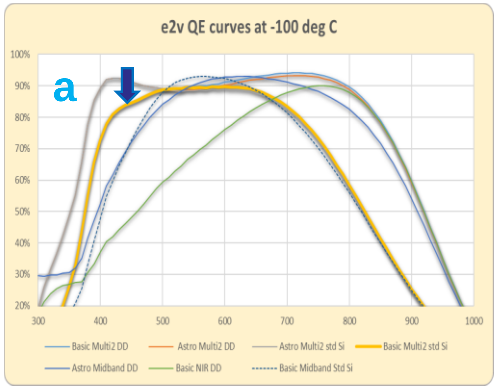
– Defined as the *standard deviation* of the combined detector noise contributions from:
  - Read noise
  - Dark current
  - Clock induced charge (CIC, where applicable)

Combined Noise	1 pixel, 100s frame, at
	0.27 e-

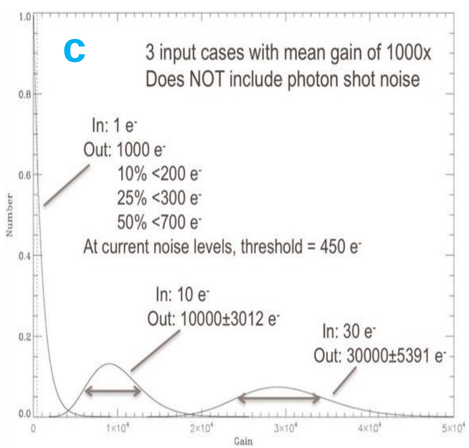
Detector Information

- **Conversion efficiency**
  - Three sources were considered
    - a. E2v QE for basic Multi2 std Si
    - b. Measured charge transfer loss in lab
    - c. Modeled threshold efficiency for photon counting





- **Total Noise**
  - Started with the phase II irradiated EMCCD representing EOL conditions:
    - read noise (assume 50e- and gain of 1000),
    - dark current as measured in lab, and
    - CIC as measured in lab.
  - Computed the sqrt of sum of variances
    - is a variance
    - is effectively a variance
    - is an effective read noise and is a standard deviation



Detector total noise in 100 s frame		
	EOL	100 s frame
read noise	5.00E-02	e/pix/fr
CIC	2.30E-03	e/pix/fr
dark current	7.00E-04	e/pix/s
total (std. dev.)	0.273	e-

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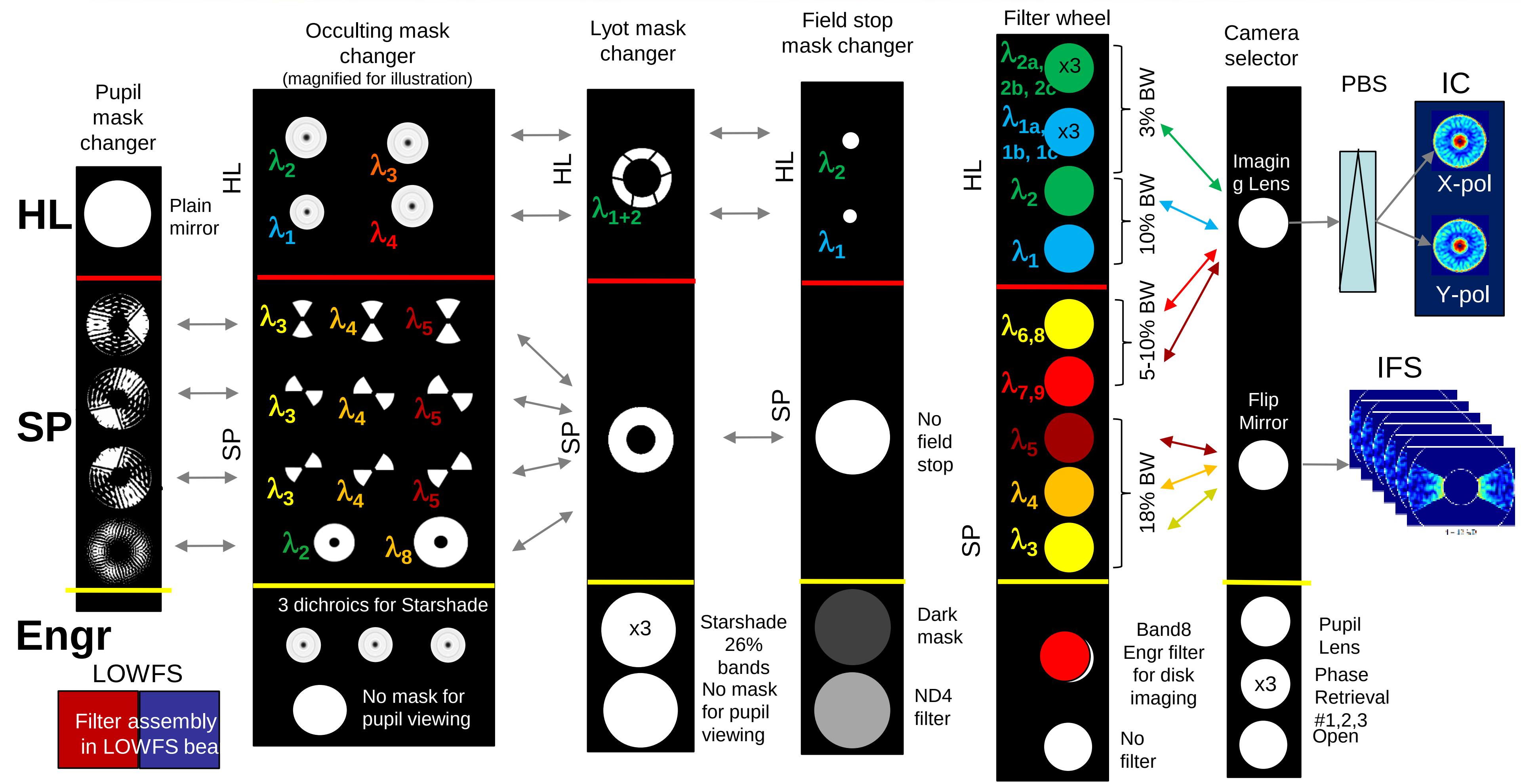
BACKUP

L3 K/D Requirements

		Key	Driving
Raw Contrast vs. working angle	8×10^{-9} 3-6 λ/D, 1×10^{-8} 6-9 λ/D **Significant recent testbed improvement (need full dynamic results)**	√	√
Contrast stability vs. working angle	5×10^{-10}, 3-9 λ/D, over 100 hours **Greatest uncertainty in terms of capability. Focus of testbed and modeling studies next year.**	√	√
Optical Throughput	≥ 1 % (TBR) of the energy entering telescope primary in core PSF (to half maximum) **Focus of ongoing design improvements**	√	√
Imaging Spatial Resolution	18.6 milliarcsec on sky / pixel **Reduced sampling to Nyquist at 430 nm based on modeling results**	√	
Spectral Filters	**Discussed in detail in previous charts**	√	
Polarization	Sequential imaging in two orthogonal polarizations	√	√
IFS Spectral Resolution	R = 50 over bandpass of 600 – 970 nm **Changed from R=70 based on SIT simulations**	√	√
IFS Spatial Sampling	26 milliarcsec on sky / lenslet **Reduced sampling to Nyquist at 600 nm based on modeling results**	√	√
IFS and Imager Detector Parameters	Read noise = 1×10^{-6} Dark current (BOL) = 3×10^{-5} CIC = 3×10^{-3} **Based on EMCCD capabilities; continuing tech development effort**	√	√

CGI Filter Wheel Populations



λ_1= 465nm λ_2=565nm λ_3=660nm λ_4=770nm λ_5=890nm

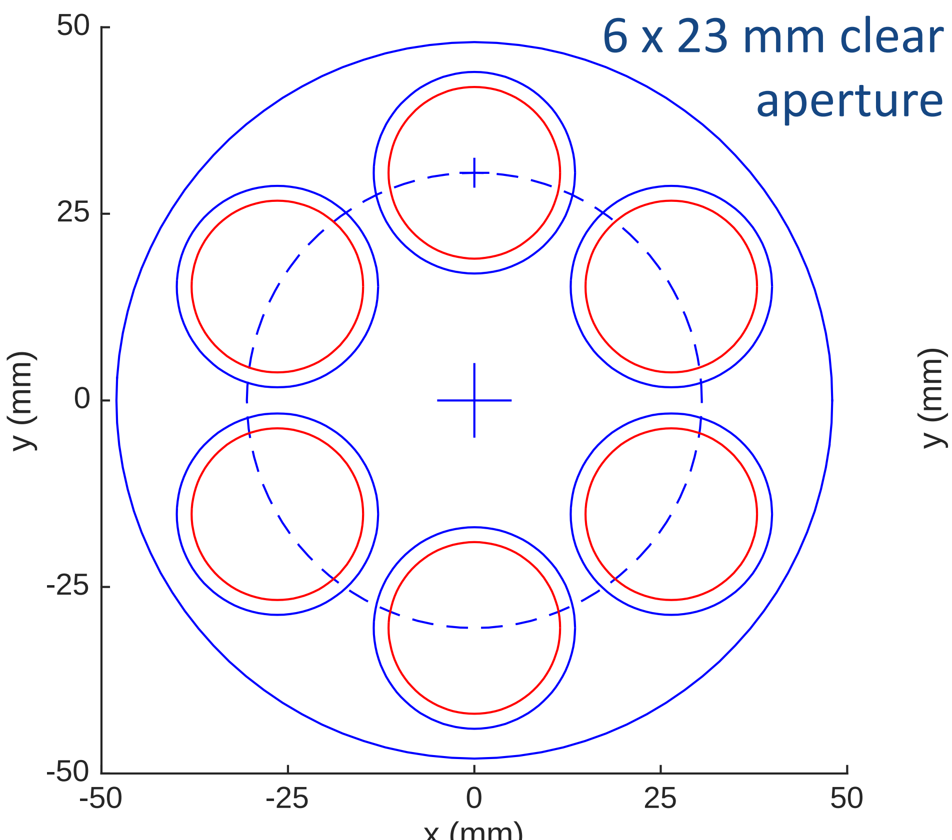
λ_{1a}= 450nm λ_{1b}= 480nm λ_{2a}=550nm λ_{2b}=580nm λ_6=661nm λ_8=721nm λ_7=883nm λ_9=950nm

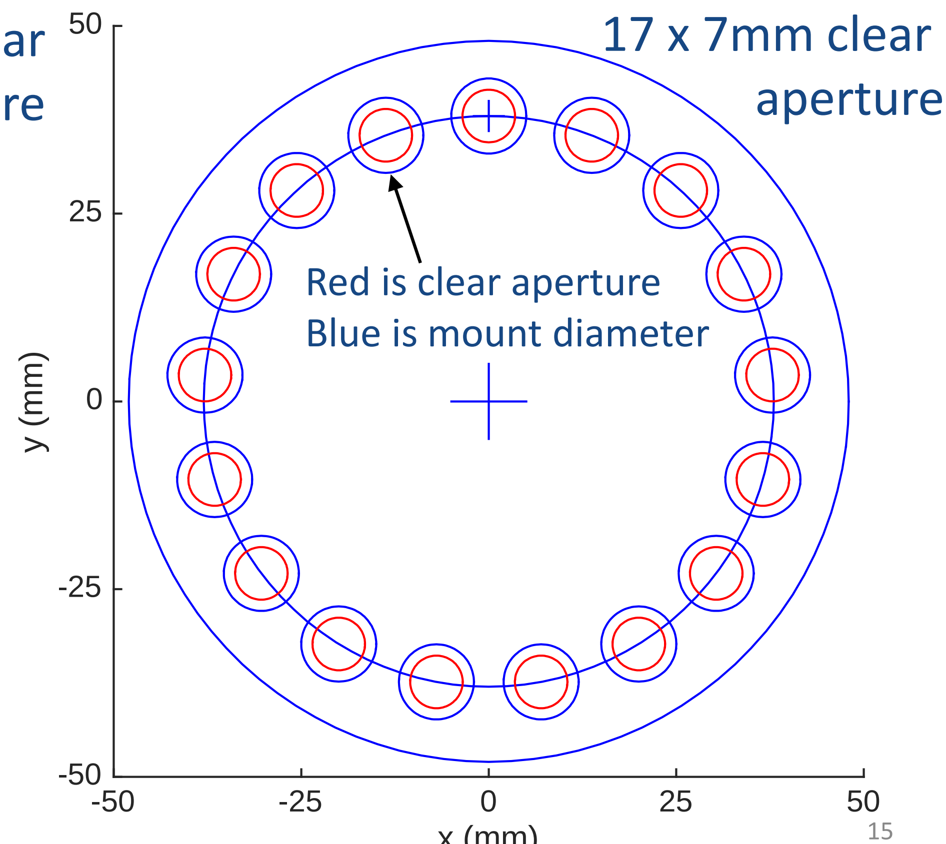
CGI Filter Wheel Populations

Slots full

Slots limited

Wheel	Beam Dia (mm)	Clear Aper. Dia. (mm)	Mount Dia (mm)	# of Occupied Slots in Current Design	Max # of Slots
Pupil Mask	20	23	27	5	6
Occulting Mask	5	7	10	17	17
Lyot Stop	20	23	27	6	6
Field Stop	5	7	10	5	17
Color Filters	5	7	10	17	17
IFS/img/pupil sel	8.5	11	14	7	12





Step 6: Estimate Planet & Disk Yields

- **Derived system throughputs (including PSF shape) along with planet/disk properties define the signal**
- **Computed speckle brightnesses, detector effects, and post-processing factors define the background noise**
- **These metrics are combined with input planet populations (e.g., known RV planets) and observing scenarios to produce planet detection and characterization yields**

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The Brightness Dependent Error Budget